Two massive stars possibly ejected from NGC 3603 via a three-body encounter

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ABSTRACT

We report the discovery of a bow-shock-producing star in the vicinity of the young massive star cluster NGC 3603 using archival data of the *Spitzer Space Telescope*. Follow-up optical spectroscopy of this star with Gemini-South led to its classification as O6 V. The orientation of the bow shock and the distance to the star (based on its spectral type) suggest that the star was expelled from the cluster, while the young age of the cluster ($\sim$2 Myr) implies that the ejection was caused by a dynamical few-body encounter in the cluster's core. The relative position on the sky of the O6 V star and a recently discovered O2 If*/WN6 star (located on the opposite side of NGC 3603) allows us to propose that both objects were ejected from the cluster via the same dynamical event – a three-body encounter between a single (O6 V) star and a massive binary (now the O2 If*/WN6 star). If our proposal is correct, then one can "weigh" the O2 If*/WN6 star using the conservation of the linear momentum. Given a mass of the O6 V star of $\approx$30 M$_\odot$, we found that at the moment of ejection the mass of the O2 If*/WN6 star was $\approx$175 M$_\odot$. Moreover, the observed X-ray luminosity of the O2 If*/WN6 star (typical of a single star) suggests that the components of this originally binary system have merged (e.g., because of encounter hardening).

Key words: stars: individual: WR 42e – stars: kinematics and dynamics – stars: massive – open clusters and associations: individual: NGC 3603

1 INTRODUCTION

Young massive star clusters lose their massive stellar content at the very beginning of their evolution because of dynamical few-body interactions (Gvaramadze, Kroupa & Pflamm-Altenburg 2010b; Fujii & Portegies Zwart 2011; Banerjee, Kroupa & Oh 2012). The ejected stars form the population of field OB stars (e.g. Gies 1987), whose space velocities range from $\sim$10 km s^{-1} (the escape velocity from the potential well of the parent cluster) to several hundreds of km s^{-1} (e.g. Heber et al. 2008). About 20 per cent of high-velocity ($>$30 km s^{-1}) field OB stars (the so-called runaway stars;

Blaauw 1961) are moving supersonically through the ambient interstellar medium (e.g. Huthoff & Kaper 2002) and produce bow shocks, which can be detected in the optical (Gull & Sofia 1979), infrared (van Buren & McCray 1988), radio (Benaglia et al. 2010), and X-ray (López-Santiago et al. 2012) wavebands.

Detection of bow shocks around massive star clusters allows us to reveal OB stars running away from these clusters (Gvaramadze & Bomans 2008; Gvaramadze et al. 2011c). Follow-up spectroscopy of stars selected in this way and the geometry of their bow shocks provide a powerful tool for linking the newly identified massive stars to their parent clusters even in those cases when the proper motion measurements for the stars are unavailable or unreliable (Gvaramadze & Bomans 2008; Gvaramadze et al. 2010a,b, 2011c; Gvaramadze, Pflamm-Altenburg & Kroupa 2011a). This in

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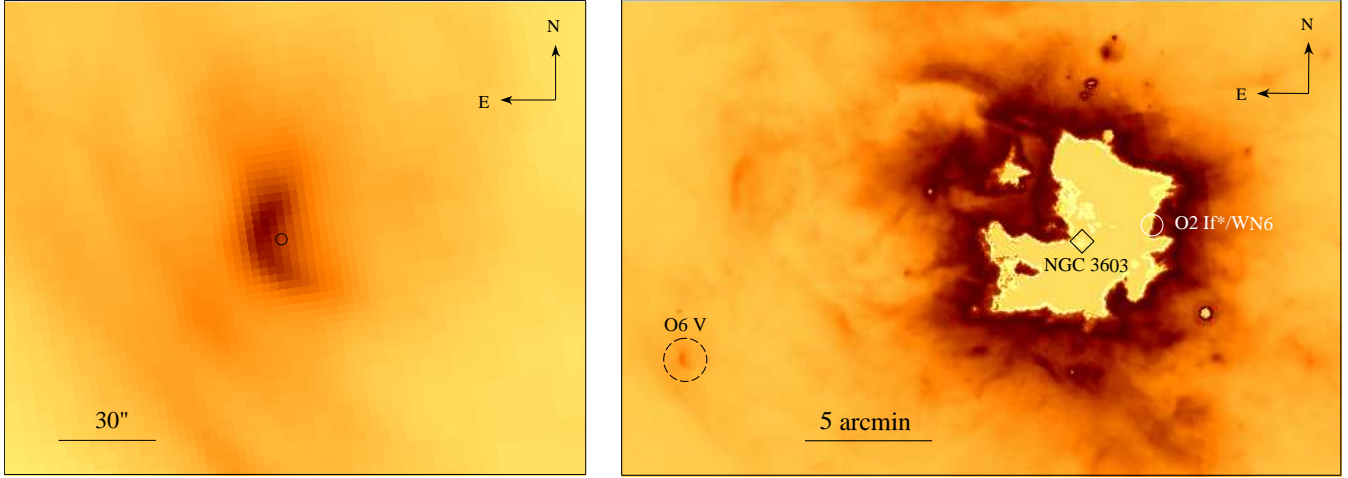
Figure 1. *Left*: MIPS 24 μm image of the bow shock detected near NGC 3603. The position of the associated O6 V star (2MASS J11171292−6120085) is marked by a circle. *Right*: MIPS 24 μm image of the highly saturated H II region associated with the star cluster NGC 3603 (indicated by a diamond). The positions of the bow-shock-producing star and the O2 If*/WN6 star (WR42e) are marked by circles (see text for details). At the distance of NGC 3603 of 7.6 kpc, 30 arcsec and 5 arcmin correspond to ≈1.1 and 10.9 pc, respectively.

turn provides useful constraints on the modelling of dynamical evolution of young star clusters (e.g. Kroupa 2008; Portegies Zwart, McMillan & Gieles 2010) and has important consequences for understanding the origin of the field OB stars (Gvaramadze et al. 2010b, 2012a). Bow shocks can also be used to constrain mass-loss rates of their associated stars (Gull & Sofia 1979; Kobulnicky, Gilbert & Kiminki 2010; Gvaramadze, Langer & Mackey 2012b) and could serve as probes of the Galactic magnetic field (Gvaramadze et al. 2011b,c).

In this Letter, we report the discovery of a bow-shock-producing star in the vicinity of the star cluster NGC 3603 (Section 2). Follow-up optical spectroscopy of this star led to its classification as O6 V (Section 3). In Section 4, we show that the relative position of the O6 V star and a recently discovered O2 If*/WN6 star on the sky is consistent with the possibility that both objects were ejected from NGC 3603 via the same dynamical event – a three-body encounter.

2   SEARCH FOR BOW SHOCKS AROUND NGC 3603

2.1   NGC 3603

NGC 3603 is a very young (∼2 Myr; Kudryavtseva et al. 2012) and one of the most massive (∼10^4 M$_\odot$; Harayama, Eisenhauer & Martins 2008) star clusters known in the Milky Way. It is located in the Carina arm at a distance of d=7.6 kpc (Melena et al. 2008). The cluster contains numerous O-type stars and three very massive WN-type stars (Moffat, Drissen & Shara 1994; Schnurr et al. 2008), whose initial masses could be as large as ≈140−170 M$_\odot$ (Crowther et al. 2010). All three WN-type stars are located in the cluster's core and two of them are short-period (≈4−9 day) binary systems (Schnurr et al. 2008).

The existence of very massive (binary) stars in the cluster and compactness of its core (the radius of the core is ≈0.2 pc; Harayama et al. 2008) suggest that, at least in the

recent past, NGC 3603 was effective in producing massive runaway stars (e.g. Gvaramadze et al. 2009; Gvaramadze & Gualandris 2011). This makes attractive a search for OB stars running away from this cluster. However, given the large distance to NGC 3603, it is unlikely that the existing astrometric catalogues would provide reliable proper motion measurements for stars ejected from the cluster, unless their peculiar velocities exceed several hundreds of km s^{-1}. The runaway status of stars around NGC 3603 can, in principle, be revealed through detection of their high peculiar radial velocities, but in the absence of reliable proper motion measurements for these stars it would be impossible to unambiguously prove their relationship to the cluster. This makes bow shocks the most important signature of massive stars running away from NGC 3603.

2.2   Bow-shock-producing star 2MASS J11171292−6120085

To search for bow shocks around NGC 3603, we used archival *Spitzer Space Telescope* 24 μm image of NGC 3603 and its surroundings (Program Id.: 41024, PI: L. Townsley) obtained with the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004). This image represents an ≈ $0°.5 × 2°.0$ strip extended almost in the eastwest direction and centred at ≈20 arcmin to the west of NGC 3603. Visual inspection of the image led to the discovery of five clear arc-like structures, which we interpret as bow shocks (cf. Gvaramadze & Bomans 2008; Gvaramadze et al. 2011c). However, only one of them is opened towards NGC 3603 (see Fig. 1) and therefore could be generated by a massive star expelled from this cluster. The stand-off distance of this bow shock is ≈7 arcsec (or ≈0.25 pc).

Subsequent examination of the Digitized Sky Survey II (DSS-II; McLean et al. 2000) red band image showed that the bow shock is apparently generated by a star with coordinates: α_{J2000}=11^{h}17^{m}12^s.93, δ_{J2000}=−61°20′08″.6, which is located at ≈0.262 degree (or ≈34 pc in projection) from
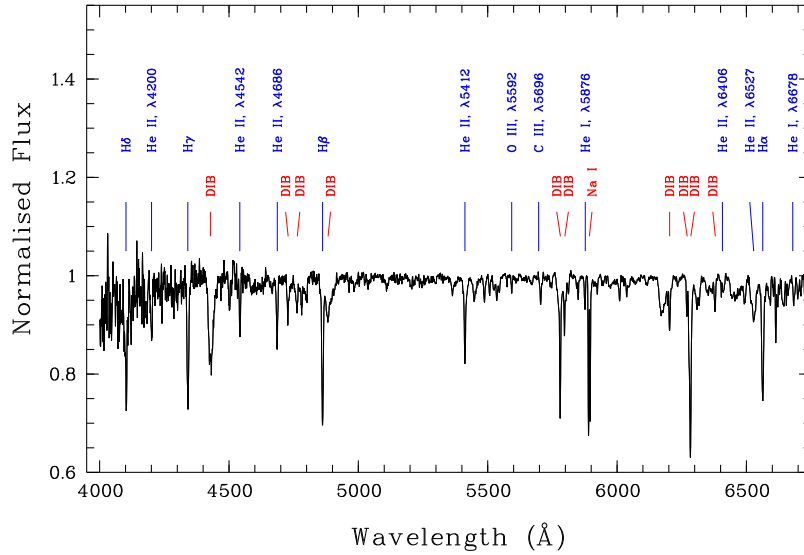
Figure 2. Normalized spectrum of 2MASS J11171292−6120085 with principal lines and most prominent DIBs indicated.

the centre of NGC 3603. This star has a visual magnitude of ≈15−16 (Zacharias et al. 2004; Lasker et al. 2008) and 2MASS (Two-Micron All Sky Survey) J, H, and K_s magnitudes of 11.79±0.03, 11.22±0.03, and 10.92±0.02, respectively (Cutri et al. 2003). In what follows, we will use for this star its 2MASS name – 2MASS J11171292−6120085, or J1117−6120, in short.

3   SPECTRAL TYPE OF J1117−6120

3.1   Spectroscopic observations and data reduction

To determine the spectral type of J1117−6120 and thereby to constrain its distance, we observed this star within the framework of our programme of spectroscopic follow-up of candidate massive stars revealed via detection of their bow shocks (e.g. Gvaramadze et al. 2011c). For observation we used the Poor Weather time at Gemini-South under the program-ID GS-2011A-Q-88. The spectroscopic follow-up was performed with the GMOS-S (Gemini Multi-Object Spectrograph South) in a long-slit mode, which provides coverage from 3800 to 6750 Å with a resolving power of ∼3000. The spectrum of J1117−6120 was collected on 2011 February 20 under fairly good conditions: with only some clouds and a ≈1 arcsec seeing. The aimed signal-to-noise ratio (S/N) of ≈150 was achieved with a total exposure time of 3×900 seconds.

The bias subtraction, flat-fielding, wavelength calibration and sky subtraction were executed with the gmos package in the gemini library of the IRAF[1] software. In order to fill the gaps in GMOS-S's CCD, the observation was divided

into three exposures obtained with a different central wavelength, i.e. with a 5 Å shift between each exposure. The extracted spectrum was obtained by averaging the individual exposures, using a sigma clipping algorithm to eliminate the effects of cosmic rays. The average wavelength resolution is ≈0.46 Å pixel^{-1} (FWHM ≈4.09 Å), and the accuracy of the wavelength calibration estimated by measuring the wavelength of ten lamp emission lines is 0.061 Å. A spectrum of the white dwarf LTT 3218 was used for flux calibration and removing the instrument response. Unfortunately, due to the weather conditions, any absolute measurement of the flux is not possible.

3.2   Spectral classification of J1117−6120

Fig. 2 presents the normalized spectrum of J1117−6120 in the $\lambda\lambda 4000 - 6750$ Å region, where most of the identified lines are marked. The spectrum is dominated by absorption lines of H I and He II, which is typical of O-type stars. He I $\lambda\lambda 5876, 6678$, O III $\lambda 5592$ and C III $\lambda 5696$ absorptions are also clearly visible in the spectrum. The relatively high interstellar extinction towards the star (≈ 6 mag; see Section 4.1) is manifested in numerous diffuse interstellar bands (DIBs). A blend of strong Na I $\lambda 5890, 96$ absorption lines is of interstellar origin as well.

The poor observational conditions and the extinction towards J1117−6120 degraded the blue part of the spectrum, which precludes us from using traditional classification criteria. Instead, we utilized the classification scheme for dwarf O stars in the yellow-green ($\lambda\lambda 4800 - 5420$ Å) proposed by Kerton, Ballantyne & Martin (1999). Using their equation (3) and the observed equivalent width (EW) of the He II $\lambda 5412$ line of 0.99±0.06 Å, we found that the star is of ≈O6 V type, although the uncertainty of the calibration leaves the possibility that it is either of O5 V or O6.5 V type. Alternatively, the spectral type of J1117−6120 can be derived using the EW(Hγ)−absolute magnitude calibration by

Balona & Crampton (1974), which for EW(Hγ)=2.28±0.06 Å gives the same spectral type of O6 V.

4   DISCUSSION

4.1   Parent cluster of J1117−6120

To estimate the distance to J1117−6120, one can use the observed photometry of this star and the synthetic photometry of Galactic O stars by Martins & Plez (2006). The existing catalogues (available through the VizieR catalogue access tool) provide quite different measurements of optical magnitudes, e.g. B=17.3 mag (USNO-A2.0; Monet 1998), V=15.7 mag (GSC2.3; Lasker et al. 2008), and B=16.2 mag and V=15.0 mag (NOMAD; Zacharias et al. 2004). In the lack of quality optical photometry, we will use only the 2MASS photometry (see Section 2.2), whose J and K_s magnitudes are consistent within the margins of error with those from the DENIS (Deep Near Infrared Survey of the Southern Sky) database (DENIS Consortium 2005).

Using the absolute K_s-band magnitude and the intrinsic $J-K_s$ colour typical of O6 V stars of −4.13 mag and −0.21 mag, respectively, we calculated the K_s-band extinction of A_{K_s}=0.71±0.02 mag and the distance to the star of $7.4^{+0.9}_{-0.5}$ kpc[2], which agrees well with the distance to NGC 3603 of 7.6 kpc. The extinction towards J1117−6120 can also be estimated by matching the dereddened spectral slope of this star with those of stars of similar effective temperature. In doing so, we found the colour excess $E(B-V)$=2.07±0.05 mag. Then using the extinction law from Rieke & Lebofsky (1985) and the standard total-to-selective absorption ratio R_V=3.1, we found A_V=6.42±0.16 mag and A_{K_s}=0.72±0.02 mag. The latter estimate is in excellent agreement with that based on the 2MASS photometry.

Alternatively, the extinction can be estimated by using the correlation between the intensity of the DIBs and $E(B-V)$ (see Herbig 1995 for a review). Using EWs of DIBs at λ5780 and λ5797 of 1.46±0.04 and 0.44±0.04 Å, respectively, and the relationships given in Herbig (1993), we calculated $E(B-V) = 2.78±0.32$ and 3.08±0.43 mag. These estimates somewhat differ from those based on the spectral slope and 2MASS photometry. This discrepancy could be caused by a foreground region of enhanced number density of carriers of the DIBs (cf. Gvaramadze et al. 2012c).

These estimates along with the orientation of the bow shock strongly suggest that NGC 3603 is the parent cluster of J1117−6120. Unfortunately, this suggestion cannot be proved by proper motion measurements because of the large distance to J1117−6120. Indeed, inspection of the VizieR database showed that none of the existing astrometric catalogues provide significant proper motion measurements for this star.

4.2   J1117−6120: a runaway star from a three-body encounter?

The young age of NGC 3603 implies that J1117−6120 was ejected dynamically, either because of a binary-binary or binary-single encounter in the cluster's core. In the first case, the most common outcome of the encounter is the exchange of the more massive components into a new eccentric binary and ejection of the less massive ones with high velocities (in general, the trajectories of the ejected stars make an arbitrary angle with each other). In the second case, a single star (usually the lowest mass star among the stars participating in the encounter) is ejected with a high velocity, while the binary system recoils in the opposite direction to the single star. In both cases, the ejected (high-velocity) stars gain their kinetic energy at the expense of the increased binding energy of the post-encounter binary, which ultimately could merge into a single star if its orbit is sufficiently compact. Thus, if J1117−6120 was ejected in the field via a three-body encounter then a massive binary or a single merged star should exist on the opposite side of NGC 3603 (cf. Gvaramadze & Gualandris 2011).

Interestingly, such a star does indeed exist. This O2 If*/WN6 star, called WR42e, was recently discovered by Roman-Lopes (2012). It is located at θ_1≈0.045 degree west-northwest of NGC 3603 (see Fig. 1), just on the opposite side of J1117−6120 (recall that this star is separated from NGC 3603 by θ_2≈0.262 degree). If both stars were ejected from NGC 3603 via a three-body encounter, then WR42e should be a very massive binary or a single merged star. Moreover, one can "weigh" this star using the conservation of the linear momentum. Assuming the mass of the O6 V star of m≈30 M$_\odot$ (e.g. Martins, Schaerer & Hillier 2005), one has that at the time of encounter the mass of the recoiled binary (now the O2 If*/WN6 star) was $M=(\theta_2/\theta_1)m$≈175 M$_\odot$.

Although the existing proper motion measurements for both stars are very unreliable[3], one can constrain their peculiar velocities using the following arguments. The minimum space velocity of a star leaving its parent cluster should exceed the escape velocity, v_{esc}, from the cluster's potential well, which for NGC 3603 is ≈10 km s^{-1} (here we assumed that at the time of the three-body encounter, say 1 Myr ago, the radius of the cluster was ∼1 pc). Correspondingly, the recoil velocity of WR 42e is $v_1 \geqslant v_{\mathrm{esc}}$, while the ejection velocity of J1117−6120 is $v_2=(\theta_2/\theta_1)v_1 \geqslant 60$ km s^{-1}. These estimates have important consequences for understanding the nature of WR42e (see next section).

The velocity estimate for J1117−6120 can also be used to constrain the number density of the ambient interstellar medium, n_0. Using the wind mass-loss rate and terminal velocity typical of O6 V stars ($\dot{M} = 10^{-7}$ M$_\odot$ yr^{-1}, v$_\infty$ = 2500 km s^{-1}; Mokiem et al. 2007), one finds $n_0 \leqslant 2.6$ cm^{-3}.

4.3   WR42e as a merged binary star

The ejection velocity of J1117−6120 should be compared with a typical ejection velocity resulting from encounters between a very massive binary and a single (less massive) star, which for binaries with equal-mass components is ≈$0.8v_{\mathrm{orb}}$ (Hills & Fullerton 1980), where v_{orb} is the orbital velocity in the binary. This comparison implies that to expel

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[2] Note the dominating source of error in the distance is the uncertainty in the spectral classification.

[3] Note that the huge proper motion of WR42e given in the PP-MXL catalogue (Röser, Demleitner & Schilbach 2010) is erroneous (S. Röser, personal communication).

J1117−6120 with the velocity of $\geqslant 60$ km s^{-1}, the binary separation should be $\leqslant 15$ AU.

A massive binary of this small separation would be a source of strong X-ray emission (e.g. Usov 1992). Following Crowther et al. (2010; see their Section 5.1 and references therein), one can estimate the expected X-ray luminosity, $L_{\rm X}^{\rm exp}$, of shocked winds in WR42e assuming that this system is composed of two equal-mass components (with the mass-loss rates of $\sim 2 \times 10^{-5}$ M$_\odot$ yr^{-1} and wind velocities of 2600 km s^{-1}) and that 10 per cent of the shock energy contributes to the X-ray emission. We found $L_{\rm X}^{\rm exp} \approx 5.6 \times 10^{34}$ erg s^{-1}, which is more than two orders of magnitude larger than the observed X-ray luminosity of WR42e of $L_{\rm X}^{\rm obs} \approx 2.3 \times 10^{32}$ erg s^{-1} (Roman-Lopes 2012). Moreover, $L_{\rm X}^{\rm obs}$ comprises a fraction of $\sim 2{-}4 \times 10^{-8}$ of the bolometric luminosity of the star (see below), which is typical of single stars (Chlebowski, Harnden & Sciortino 1989). From this it follows that WR42e might be a merger product of the recoiled binary system, which is coalesced because of the encounter hardening.

Numerical simulations by Suzuki et al. (2007) showed that during the merger process the system loses about 10 per cent of its mass, which in the case of WR42e corresponds to ~ 20 M$_\odot$. The resulting very massive star is a fast rotator with higher-than-average helium abundance, which might be responsible for the Of*/WN-type spectrum of WR42e (cf. Walborn et al. 2010). During the subsequent ~ 1 Myr the star additionally loses about $20{-}30$ M$_\odot$ in the form of stellar wind, so that its current mass should be $\approx 125{-}135$ M$_\odot$, which corresponds to a luminosity of $\log(L/L_\odot) \approx 6.3{-}6.5$ (Crowther et al. 2010; Ekström et al. 2012). This value should be compared with the luminosity of WR42e. Using the 2MASS J and $K_{\rm s}$ magnitudes of this star of 10.18 and 9.04, respectively, and $(J-K_{\rm s})_0 = -0.21$ mag (Martins & Plez 2006), one finds $M_{K_{\rm s}} = -6.25$ mag, which for the K-band bolometric correction of $-(4.4 \div 5.2)$ mag (Crowther & Walborn 2011) corresponds to $\log(L/L_\odot) \approx 6.2{-}6.5$ (cf. Roman-Lopes (2012).

To conclude, if our proposal on the relationship between J1117−6120 and WR42e is correct then one can expect that the peculiar radial velocity of the latter star should be about six times smaller than that of the former one. For J1117−6120 we measured a heliocentric radial velocity of 21.4 ± 6.3 km s^{-1}, which is an average over the hydrogen and He II lines. After correction for the Galactic differential rotation and the solar peculiar motion, we found the peculiar radial velocity of J1117−6120 of -4.8 km s^{-1}, i.e. the star is moving almost in the plane of sky. [This estimate was derived using the Galactic constants $R_0 = 8.0$ kpc and $\Theta_0 = 240$ km s^{-1} (Reid et al. 2009) and the solar peculiar motion $(U_\odot, V_\odot, W_\odot) = (11.1, 12.2, 7.3)$ km s^{-1} (Schönrich, Binney & Dehnen 2010).] Correspondingly, the peculiar radial velocity of WR42e should also be almost zero. Radial velocity measurements for WR42e are therefore of crucial importance for testing our proposal.

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